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# Reduction of efficiency droop in InGaN light emitting diodes by coupled quantum wells

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Light emitting diodes (LEDs) based on InGaN suffer from efficiency droop at current injection levels as low as  $50 \text{ A cm}^{-2}$ . We investigated multiple quantum well InGaN LEDs with varying InGaN barrier thicknesses (3–12 nm) emitting at  $\sim 400\text{--}410 \text{ nm}$  to investigate the effect of hole mass and also to find out possible solutions to prevent the efficiency droop. In LEDs with electron blocking layers, when we reduced the InGaN barriers from 12 to 3 nm, the current density for the peak or saturation of external quantum efficiency increased from 200 to  $1100 \text{ A cm}^{-2}$  under pulsed injection conditions, which eliminates the heating effects to a large extent. Our calculations show that such reduction in the barrier thickness makes the hole distribution more uniform among the wells. These results suggest that the inferior low hole transport through the barriers exacerbated by large hole effective mass and low hole injection due to relatively low hole concentration and the consequent electron leakage are responsible for the efficiency droop at high current injection levels. © 2008 American Institute of Physics. [DOI: 10.1063/1.3012388]

Nitride-based light emitting diodes (LEDs) suffer from the reduction in efficiency at high injection current levels, a property which has been dubbed the “efficiency droop.”<sup>1,2</sup> It is imperative to overcome this problem to allow LEDs to produce high luminous flux with reasonably high efficiencies at high current densities for use in lighting. Various models for the efficiency droop have been proposed, including “current rollover,”<sup>3</sup> limited carrier injection efficiency,<sup>4,5</sup> polarization field,<sup>6,7</sup> Auger recombination,<sup>8</sup> and junction heating.<sup>9</sup> Although proposed to cause the efficiency droop,<sup>8</sup> the Auger losses in wide bandgap semiconductors are expected to be very small,<sup>10</sup> as verified by fully microscopic many body models.<sup>11</sup> Moreover, the absence of efficiency droop in photoexcitation experiments where carriers are excited only in the quantum wells (QWs) with generation rates comparable to or even higher than high electrical injection indicates that efficiency droop is related to the skewed carrier injection, transport, and leakage processes.<sup>6,12</sup>

As we reported in Ref. 12, by employing *p*-type doped barriers or by using a lightly *n*-type doped GaN injection layer just below the InGaN multiple quantum wells (MQWs) at the *n* side, intended to bring electron and hole injection to comparable levels, the efficiency droop could be shifted to higher current levels, 900 and  $550 \text{ A cm}^{-2}$ , respectively.<sup>12</sup> These results suggest that poor hole transport and injection through the barrier due to large hole effective mass and low hole concentration (limited by technology) leading to serious electron leakage without contributing to radiative recombination are the main responsible mechanisms for the observed efficiency droop.

In the studies where the polarization charge has been proposed as the reason for electron leakage and thus efficiency droop,<sup>6,7</sup> LEDs with GaN barriers have been used. Notice that in our earlier work<sup>12</sup> LEDs with undoped GaN barriers were shown to exhibit efficiency peaks at signifi-

cantly lower current densities compared to those with InGaN barriers (35 and  $220 \text{ A/cm}^2$ , respectively). In addition, the thick GaN:Si barriers (18 nm) used in Ref. 6 were also expected to deteriorate the hole transport throughout the active region further. By using AlGaInN instead of GaN for barriers (3 nm thick) to reduce the polarization mismatch between the QW and the barrier, the efficiency peak has been observed to shift from  $5 \text{ A/cm}^2$  to only  $22 \text{ A/cm}^2$ ,<sup>7</sup> which is still more than an order of magnitude lower than what we reported for LEDs with InGaN barriers.<sup>12</sup>

Ideally, even though elimination of the MQW in favor of a double heterostructure LED would be desirable, technological issues dovetailed possibly with other issues prevent competitive LEDs to be obtained. Limited, therefore, to MQWs in the present effort, we demonstrate that the efficiency droop could be shifted to a much higher current density ( $1100 \text{ A cm}^{-2}$  or higher) by reducing the barrier width to 3 nm when compared to that in a reference LED sample with 12 nm barriers ( $200 \text{ A cm}^{-2}$ ).

The InGaN/InGaN MQW LED samples (emitting at  $\sim 400\text{--}410 \text{ nm}$ ) were grown on (0001) sapphire substrates in a vertical low-pressure metalorganic chemical vapor deposition system.<sup>12</sup> The GaN buffer layers with  $\sim 2 \times 10^8 \text{ cm}^{-2}$  dislocation density, prepared with *in situ* SiN<sub>x</sub>-mediated epitaxial lateral overgrowth, served as templates.<sup>13</sup> The schematic of the typical LED structures is shown in Fig. 1. The upper portion of the templates is 1- $\mu\text{m}$ -thick *n*-GaN with  $2 \times 10^{18} \text{ cm}^{-3}$  doping. For comparison, in one sample the upper portion of the template was also In doped with a trimethylindium (TMIn) flow rate of  $46 \mu\text{mol/min}$ . The active regions in all samples are composed of six 2-nm-thick undoped In<sub>0.14</sub>Ga<sub>0.86</sub>N QWs separated by 3- or 12-nm-thick undoped In<sub>0.01</sub>Ga<sub>0.99</sub>N barriers grown on  $\sim 60\text{-nm}$ -thick Si-doped ( $\sim 2 \times 10^{18} \text{ cm}^{-3}$ ) In<sub>0.01</sub>Ga<sub>0.99</sub>N interlayer (compliance layer) used for strain relaxation (but most likely is a quality enhancer). An  $\sim 10 \text{ nm}$  *p*-Al<sub>0.15</sub>Ga<sub>0.85</sub>N electron blocking layer was incorporated on top of the active MQW region. The *p*-GaN layer that followed is about 120 nm thick

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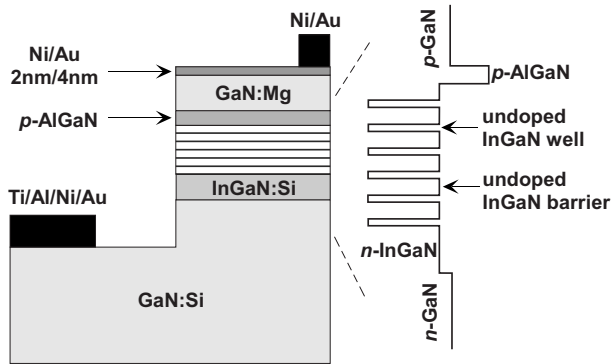


FIG. 1. Schematic diagram of LED structures investigated. In all the samples, the 2 nm InGaIn QWs were undoped, and the InGaIn barriers were also undoped with a thickness of 3 or 12 nm. An  $\sim 10$  nm  $p\text{-Al}_{0.15}\text{Ga}_{0.85}\text{In}$  was included as an electron blocking layer in all the samples.

with  $1 \times 10^{18} \text{ cm}^{-3}$  doping (Mg). After mesa (250  $\mu\text{m}$  diameter) etching, Ti/Al/Ni/Au (30/100/30/30 nm) metallization annealed at 850  $^{\circ}\text{C}$  for 30 s was used for  $n$ -Ohmic contacts, and 2 nm/4 nm semitransparent Ni/Au layer was used for  $p$ -contacts. Finally, a 30 nm/30 nm Ni/Au contact pad was deposited on part of the top of the mesa (albeit with opacity) for probe contacts.

In order to investigate the carrier transport within LED devices, simulations of the band diagram and charge distribution were performed using the APSYS software. A modified drift-diffusion model with corrections such as quantum tunneling/capture/escape and direct flight mechanisms, spontaneous and piezoelectric polarization fields, and a doping and field-dependent mobility model specific to nitrides has been applied. A recombination lifetime of 1 ns, an Auger recombination coefficient of  $1 \times 10^{-34} \text{ cm}^6 \text{ s}^{-1}$ , and spontaneous and piezoelectric polarization charge densities of  $5.8 \times 10^{12}$  and  $8.7 \times 10^{12} \text{ cm}^{-2}$  at the interfaces between the wells and barriers in the MQW region, respectively, were used. It is assumed that the wells are partially relaxed for the 3 nm barrier case and fully strained for the 12 nm barrier case. Figure 2 shows the calculated band diagrams at a forward bias of +6 V (560 and 500  $\text{A cm}^{-2}$  for the 3 and 12 nm barrier LEDs, respectively) together with hole distributions within the QWs.

As can be seen from Fig. 2(a), in the 12 nm barrier case, the hole concentration in the QW near the  $p$ -side is around seven orders of magnitude higher than that in the QW adjacent to the  $n$ -side. This means that most of the recombination occurs only within the first QW close to the  $p$ -side. As shown in Fig. 2(b), depicting the barrier thickness of 3 nm, the holes are uniformly distributed across all the QWs with an average density of  $3 \times 10^{15} \text{ cm}^{-3}$ . Therefore, all the wells participate in the recombination process. The overall hole concentration injected into the QWs is approximately the same for both 12 and 3 nm barrier LED structures. The calculations confirm that reducing the barrier thickness enhances the hole distribution across all the QWs where they recombine efficiently with electrons. Efficient recombination with electrons in all the QWs thereby reduces the excess electron density and thus the electron leakage at high injection currents, which improves the light output. The trend thus described remains the same for larger biases and current levels as well.

The electroluminescence (EL) spectra of the LEDs were measured using a pulsed current source with 1% duty cycle

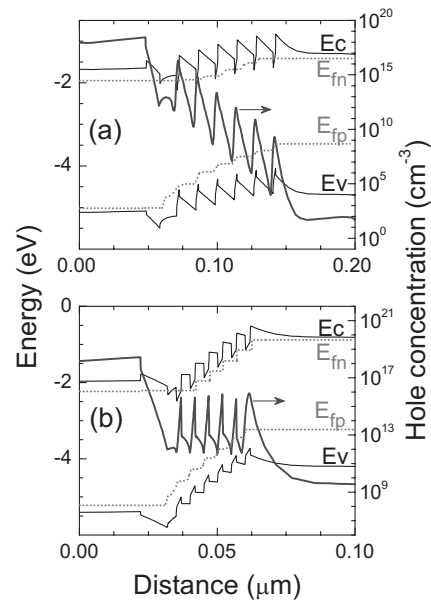


FIG. 2. Calculated band diagrams for LEDs with (a) 12 and (b) 3 nm InGaIn barriers under +6 V forward bias at 300 K. Also shown are the hole distributions within the QWs (thick solid lines). Dashed lines represent quasi-Fermi levels.

and 1 kHz frequency in order to eliminate the heating effect. To further minimize heating, the samples were mounted on a heat sink with thermoelectric cooling, and nitrogen gas was blown directly on the sample surface during measurements. Light was collected by an optical fiber placed above the diode and connected to a computer controlled spectrometer equipped with a charge coupled device detector. The integrated EL intensity versus injection current density, together with the extracted relative external quantum efficiency (EQE), for the LED samples with 3- and 12-nm-thick undoped InGaIn barriers is plotted in Fig. 3.

In the case of 12-nm-thick InGaIn barriers, the EQE reached its peak value at a current density of 200  $\text{A cm}^{-2}$ . When the thickness of the barrier was reduced to 3 nm, the EQE is observed to reach a peak value at a significantly higher current density of around 1100  $\text{A cm}^{-2}$ , followed by a gradual decline which we believe is partially due to degraded top Ohmic contact, which has not been optimized for use under extremely high current density. More interestingly, for 3 nm barriers in some devices the EQE was observed to

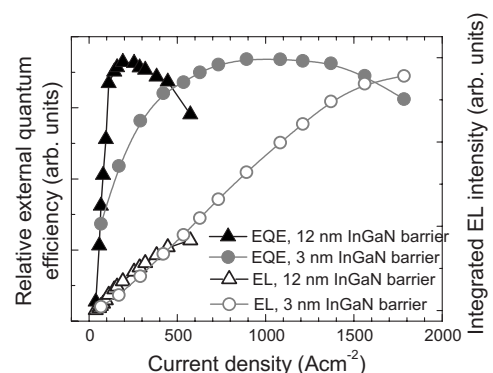


FIG. 3. Integrated EL intensity (open symbols) and normalized relative EQE (solid symbols) as functions of current density measured under pulsed conditions (1% duty cycle, 1 kHz) for LED structures with 12 and 3 nm undoped InGaIn barriers.

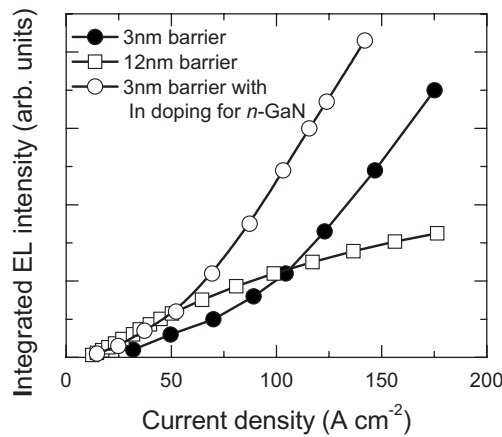


FIG. 4. EL intensity as a function of dc current density measured for LED structures with 12 and 3 nm undoped InGaN barriers. Also shown are the data for the 3 nm barrier LED sample where the top  $1\ \mu\text{m}$   $n\text{-GaIn}$  of the template is doped with In.

gradually saturate at a current density of  $1100\ \text{A cm}^{-2}$ , and then remain nearly constant up to  $2000\ \text{A cm}^{-2}$ , where the Ohmic contacts begin to degrade. Therefore, for our devices we suggest that the onset of efficiency droop would be possibly beyond  $2000\ \text{A cm}^{-2}$ . The data obtained are consistent with calculations in that reducing the barrier thickness to a level where the wells are coupled enhances the hole transport through the barriers and increases recombination with injected electrons, thereby reducing the electron leakage at high current levels and improving the quantum efficiency. It should also be mentioned that even if the phonon-assisted Auger recombination were effective as suggested by some researchers, its effect in all of our samples would be similar and thus the conclusions of our comparative study would still hold.

In order to also study the absolute effect of barrier thickness on the quantum efficiency, comparison of integrated EL intensity has been made between the LED samples with 12 and 3 nm InGaN barriers under dc bias. The EL intensity versus injection current was measured by using a calibrated Si detector, where the light was collected from the top of the LEDs through a microscope with a  $5\times$  objective. As shown in Fig. 4, the EL intensity of a typical LED with 12 nm barriers is stronger than that with 3 nm barriers until the current density reaches about  $100\ \text{A cm}^{-2}$ . As the current is increased further, however, the EL intensity from the thicker barrier sample increases sublinearly and becomes weaker than that from the sample with 3 nm barriers. At a current density of  $175\ \text{A cm}^{-2}$ , the EL intensity for the 12 nm barrier LED sample is only half of that with 3 nm barriers. No sublinearity was observed in the EL intensity of the LED sample with 3 nm barriers up to the maximum drive current employed, which was limited by destruction of Ohmic contacts due to excessive heating. This further confirms that the peak efficiency for this LED sample occurs at a much higher driving current than that for the control LED sample with 12 nm barriers. We also studied the effect of indium doping on the LED performance (open circles in Fig. 4) since it has been reported that In doping could help reduce the threading dislocations and point defects, and therefore, improve the

radiative recombination efficiency.<sup>14,15</sup> Our results show that for 3 nm barriers and In-doped top layer of the GaN template, the EL intensity at a dc current density of  $140\ \text{A cm}^{-2}$  (highest measurement point limited by contacts) is twice as high as that for the comparable LED sample without In doping and three times that of the LED with 12 nm barriers at the same injection current. Furthermore, under pulsed drive conditions the peak efficiency occurred at around  $1100\ \text{A cm}^{-2}$  for this In-doped sample, which is similar to that for the sample with no In doping. Therefore, In doping of the template improves the absolute EQE of the LEDs but not the current at which the droop occurs.

In summary, by reducing the InGaN barrier thickness from 12 to 3 nm, the onset of EQE droop was extended from 200 to  $1100\ \text{A cm}^{-2}$ . In some devices we observed only saturation of EQE up to a current density of  $2000\ \text{A cm}^{-2}$ , limited by degradation of Ohmic contacts. We, therefore, suggest that the current at which droop occurs in narrow barriers may be even higher than  $2000\ \text{A cm}^{-2}$ . Calculations showed poor population of holes within QWs in devices with 12 nm barriers and uniform hole population for those with 3 nm barriers. The data together with calculations confirm that poor hole transport through barriers and concomitant excess electrons and thus electron leakage are responsible for the efficiency droop occurring at high injection currents.

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